Real Accelerators.
Errors and Diagnostics.

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Introduction

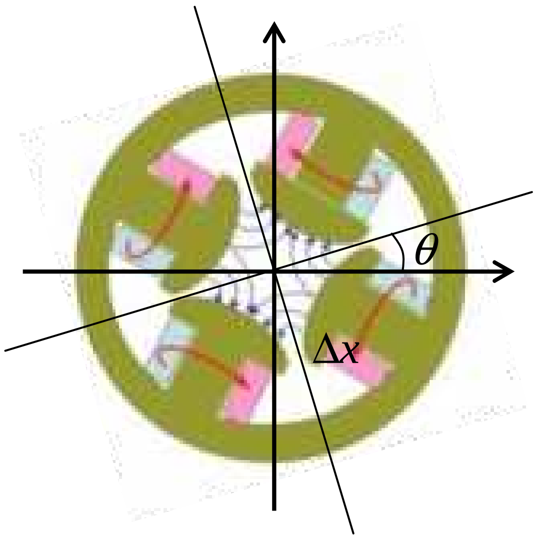
• In designing and constructing an accelerator, physicists and engineers do their best in making a perfect job and in foreseeing any possible operation mode for their device.

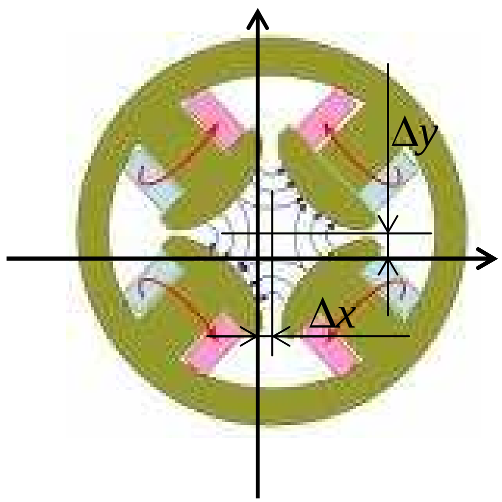
• In most of the cases, the *ideal machine* remains just a concept and one has to deal with more real objects where construction tolerances and unpredicted phenomena generate effects that need to be measured and corrected.

• In this lecture, we will briefly introduce the more typical (and predictable) errors affecting real accelerators. We will also discuss with some more details examples (not a complete list) of diagnostic systems and beam measurements used for correcting for those errors.

Magnet Misalignment Effects

A multipole of order n, with a tilt error will present a "skew" component of order n with amplitude proportional to the tilt angle.





A multipole of order n, with a displacement error will present *all the multipolar components with order* $i = 1, 2, \ldots, n - 1$.

Dipole Error Component Effect

- We saw that a displacement error in a magnet generates a **dipole component** in its center. This term induces a beam **orbit distortion.**
- If we have dipolar errors in N different ring locations, they generate N kicks θ_i and a total orbit distortion given by:

Betatron phases

$$w(s) = \frac{\sqrt{\beta_w(s)}}{2\sin(\pi\nu_w)} \sum_{i=1}^{N} \sqrt{\beta_w(s_i)}\theta_i \cos\nu_w\left[\left|\varphi(s)-\varphi(s_i)\right|+\pi\right] \qquad w = x, y$$

- Note that for integer tunes no closed orbit exists.

- Because of radiation damping, positrons and electrons converge into the distorted orbit in roughly a damping time. Protons and heavier particles oscillates around the distorted closed orbit without converging into it.

- In the case of a single kick at the position s, the displacement induced the kick at the same point s is given by:

$$w(s) = \frac{1}{2}\beta_w(s)\theta \cot\nu_w\pi \qquad w = x, y$$

- If a *corrector or steering magnet* (small dipole magnet capable of generating a kick θ) has a *beam position monitor* (BPM) nearby, by kicking the beam and using the previous relation, the beta function at that point can be measured.

Orbit Correction Basics

By measuring the orbit distortion in N BPMs along the ring, we find the set of displacements:

$$\mathbf{u}_N = \{u_1, u_2, \ldots, u_N\}$$

By using M correctors magnets, we can find a set of kicks that cancels the displacement of the beam at the BPM positions. This is obtained when:

$$-u_j = \frac{\sqrt{\beta(s_j)}}{2\sin(\pi\nu)} \sum_{i=1}^{M} \sqrt{\beta(s_i)}\ \theta_i \cos\nu\left[\left|\varphi(s_j) - \varphi(s_i)\right| + \pi\right] \qquad j = 1, 2, \ldots, N$$

Or in matrix representation, when:

$$-\mathbf{u}_N = \mathbf{M}\boldsymbol{\theta}_M \qquad with \quad M_{ji} = \frac{\sqrt{\beta(s_j)\beta(s_i)}}{2\sin(\pi\nu)} \cos\nu\left[\left|\varphi(s_j) - \varphi(s_i)\right| + \pi\right]$$

The kicks that need to be applied to the steering magnets for correcting the closed orbit distortion, can be obtained by inverting the previous equation:

$$\boxed{\boldsymbol{\theta}_M = -\mathbf{M}^{-1}\mathbf{u}_N}$$

The elements of the response matrix $\mathbf{M}$, can be calculated from the machine model, or measured by individually exciting each of the correctors and measuring the induced displacement in each of the BPMs.

Quadrupole Error Component Effect

Quadrupole error components (gradient errors) can be due to misalignment of higher order multipolar magnet (sextupoles, octupoles, …) or due to error in the current-strength calibration of quadrupole magnets.

Gradient errors generate a betatron tune shift equal to:

$$\Delta\nu \cong \frac{\beta}{2\pi} k_Q L \qquad \text{where } k_Q = \frac{Gq}{p_0} = \text{quadrupole strength}$$

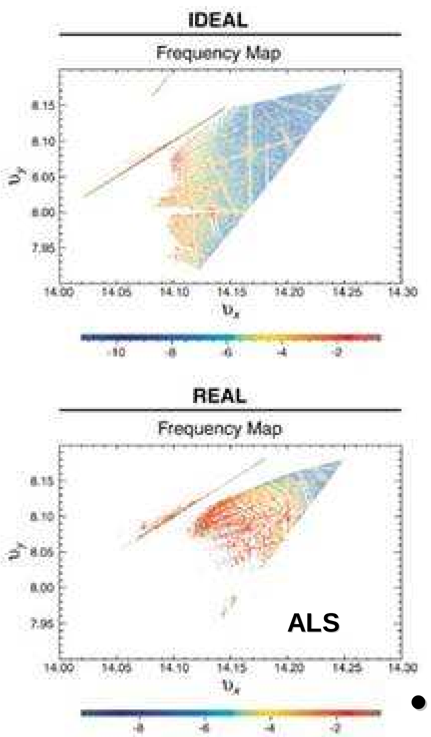
L is the quadrupole magnetic length, G is its gradient and q and p_0 are the particle charge and momentum respectively. The previous equation can be used for measuring the beta function at the quadrupole position, when the tune shift for small change of the magnet strength is measured.

It can be shown that quadrupole gradient errors makes the half-integer resonance unstable.

Tilt errors in quadrupole magnets generate coupling between the vertical and the horizontal planes. On the other hand, on purpose tilted quadrupoles (*skew quadrupoles*) can be used for compensating the coupling due to lattice non-linearities.

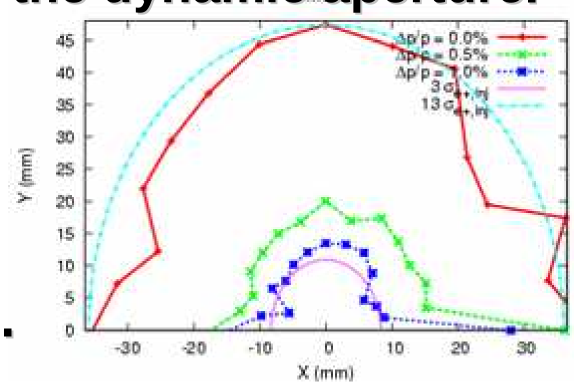
Non-ideal Magnets: Multipolar Terms

• **Simplified geometries, imperfections and mechanical tolerances in the design and construction of accelerator magnets, populates the accelerators with a plethora of higher order multipolar terms.**



• **Good design and construction can minimize but not cancel the multipolar field presence. Additionally, in most of storage rings sextupole (and sometimes octupole) magnets are added on purpose for the compensation of chromatic effects and for improving the dynamic aperture.**

• **Multipolar field components introduce non-linearities that generate a shift in the betatron frequency for large amplitude oscillations (tune shift on amplitude).**



• **These tune shifts can bring particles on tune resonances generating particle losses (*dynamic aperture*).**

• **On the other hand, these frequency shifts generate de-coherence in the oscillations with a damping effect on instabilities (*Landau damping*).**

Power Supply Fluctuations

• **Fluctuations in the power supply current** of the accelerator magnets can limit the performance of an accelerator.

• Jitter in the dipole magnet power supplies generates fluctuations in the beam energy inducing jitter in the tunes and orbit fluctuations as well.

• Jitter on quadrupole magnet power supplies generate betatron tune fluctuations that can bring particles on tune resonances and generate particle losses.

• Any power supply fluctuation will be transferred to beam (amplified in the case of strong focusing machines) affecting the ultimate performance of the accelerators.

• Power supply stability requirements strongly depend on which part of the accelerator the magnet is located.

Typical relative stability requirements range from few units of 10^{-3} for beam transfer-lines power supplies to about 10^{-5} for the case of storage ring power supplies.

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Other Perturbations

- **Several other perturbations can affect the proper operation of an accelerator.**

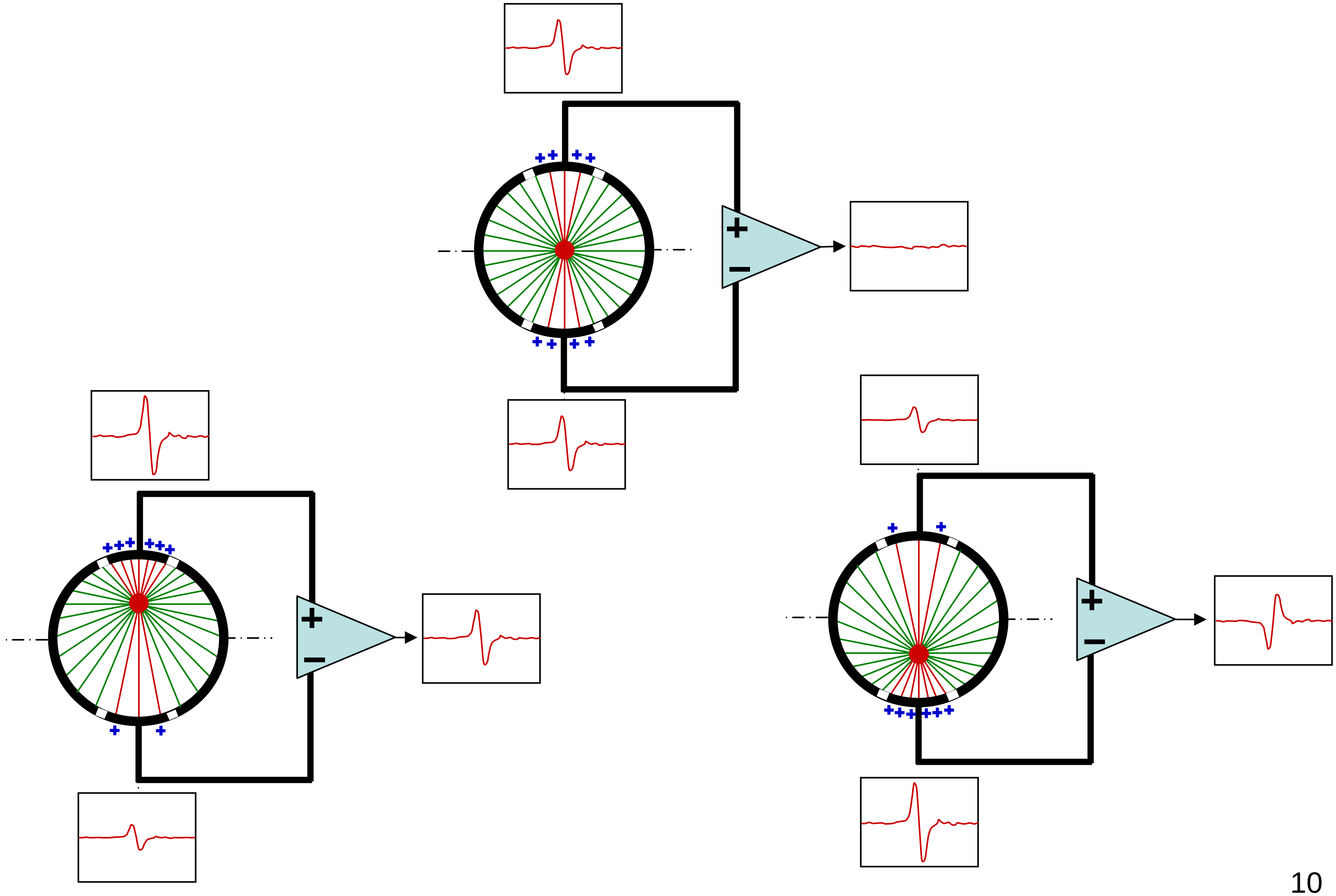
- **Very large accelerators are sensitive to the earth magnetic field, to the moon phases, to neighbor railway stations, …**

- **All accelerators are sensitive to environmental fields and variables: stray magnetic fields due to equipment or to high power electric cables, presence of other accelerators, temperature variations, fluctuations of the main AC power, ground motion, vibrations, …**

- **Last but not least, accelerators are designed for specific applications that often require detectors using high magnetic fields.**
This is the typical case for high energy physics experiments in colliders, or of insertion devices for radiation production in light sources. These fields if not compensated can have a strong impact on the accelerator performance.

- **In order to minimize and compensate for the effects due to all these perturbations and errors, an efficient beam diagnostics system need to be used.**

Electromagnetic Beam Position Monitors

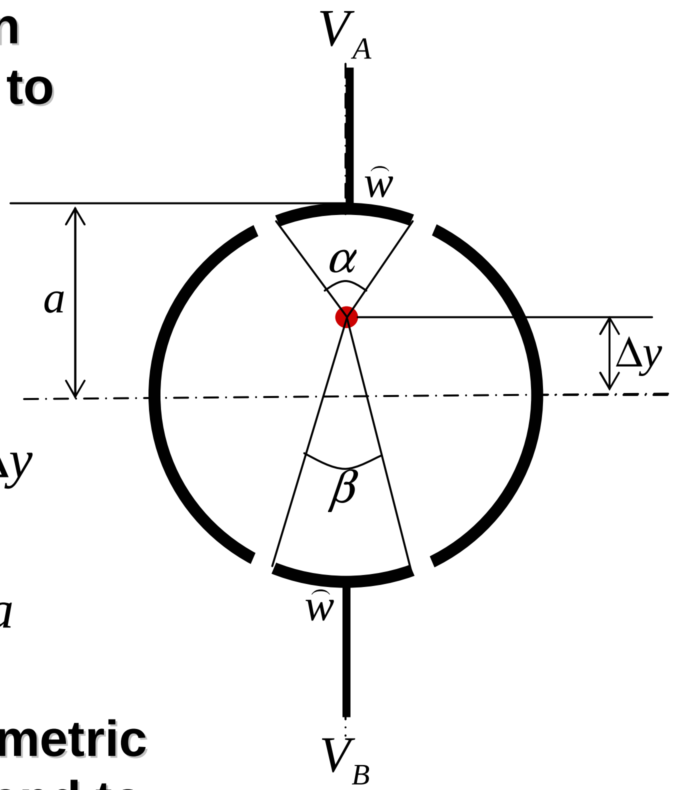


Electromagnetic Beam Position Monitors

In electromagnetic BPMs, the image charge in an electrode is proportional to the beam current and to the angle included between the beam and the electrode extremes:

$$V_A = G\,I\,\alpha$$
$$V_B = G\,I\,\beta$$

$$But \quad \widehat{w} = \alpha(a - \Delta y) = \beta(a + \Delta y)$$



$$V_A = G\,I\,\frac{\widehat{w}}{a - \Delta y} \qquad V_B = G\,I\,\frac{\widehat{w}}{a + \Delta y}$$

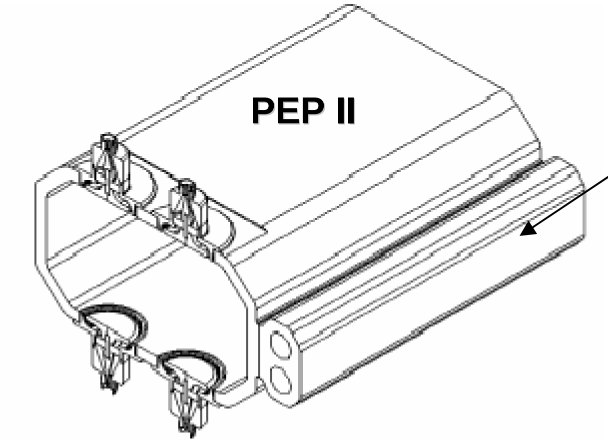
$$V_A - V_B = \frac{2G\,\widehat{w}}{a^2 - \Delta y^2}\,I\,\Delta y \qquad V_A + V_B = \frac{2G\,\widehat{w}}{a^2 - \Delta y^2}\,I\,a$$

$$\frac{V_A - V_B}{V_A + V_B} = \frac{\Delta y}{a}$$

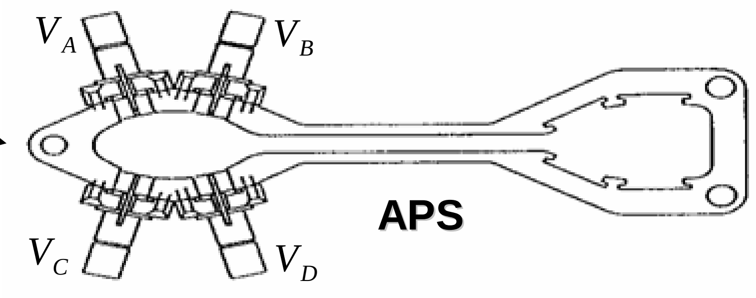
In addition to this geometric effect, the field lines tend to cluster closely in the region of the nearest electrode (the *E* field must be perpendicular to the walls). For this geometry, this gives an additional factor two:

$$\boxed{\Delta y \cong \frac{a}{2}\,\frac{V_A - V_B}{V_A + V_B}}$$

"Button" Type BPMs

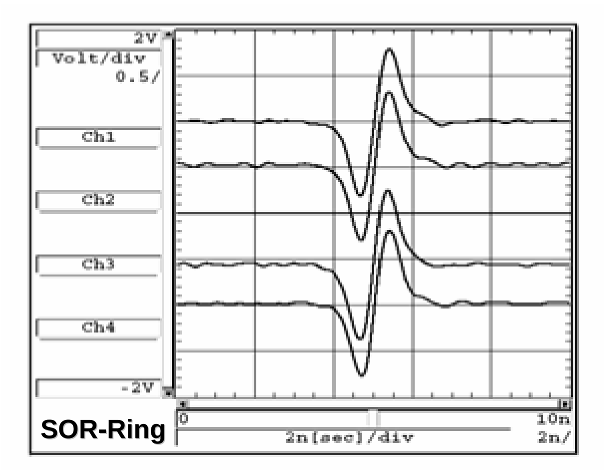


• **Typical geometry used in the presence of synchrotron radiation.**

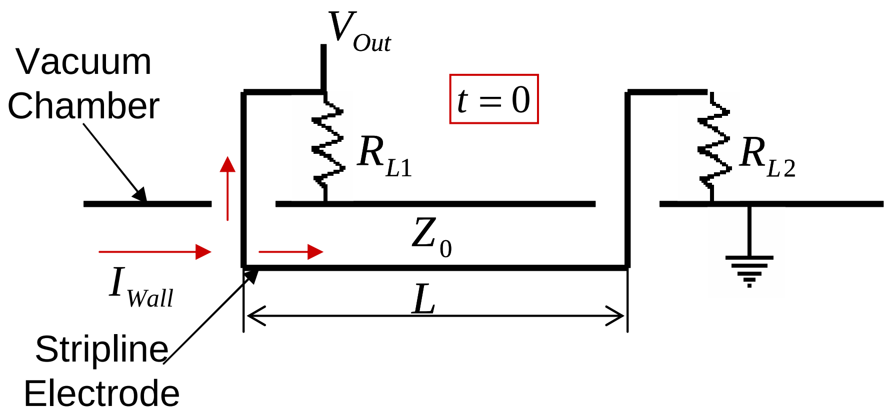


$$\Delta x = K\frac{(V_A+V_C)-(V_B+V_D)}{V_A+V_B+V_C+V_D}, \qquad \Delta y = K\frac{(V_A+V_B)-(V_C+V_D)}{V_A+V_B+V_C+V_D}$$

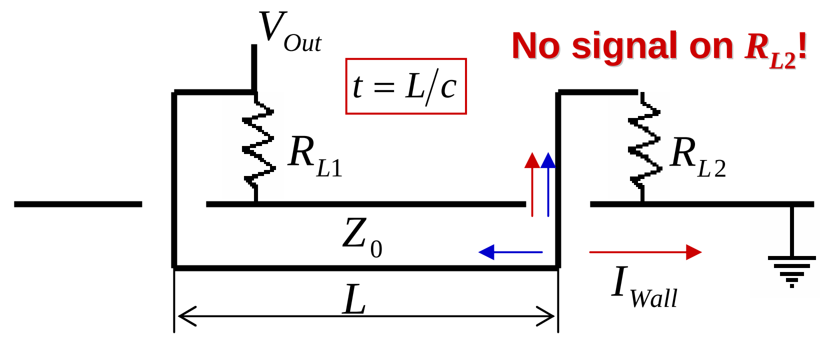
• **Capacitive type (derivative response), low coupling impedance, relatively low sensitivity, best for storage rings.**



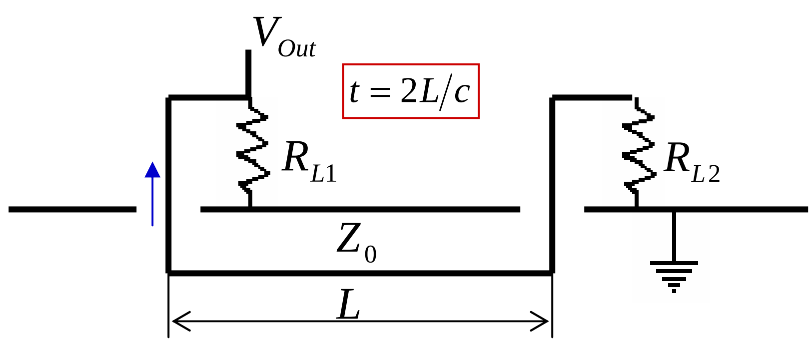
Stripline Electrode



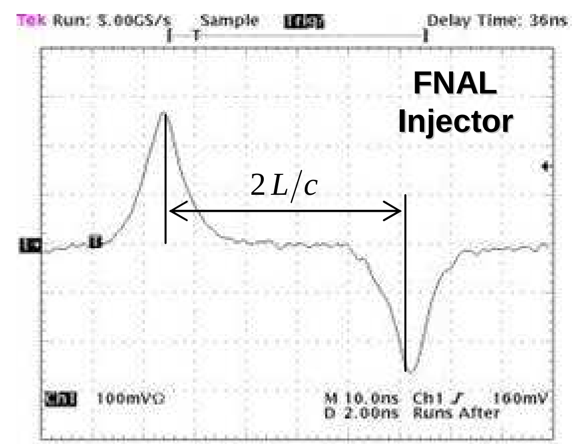
No signal on R_{L2}!



Blue color: inverted polarity pulse

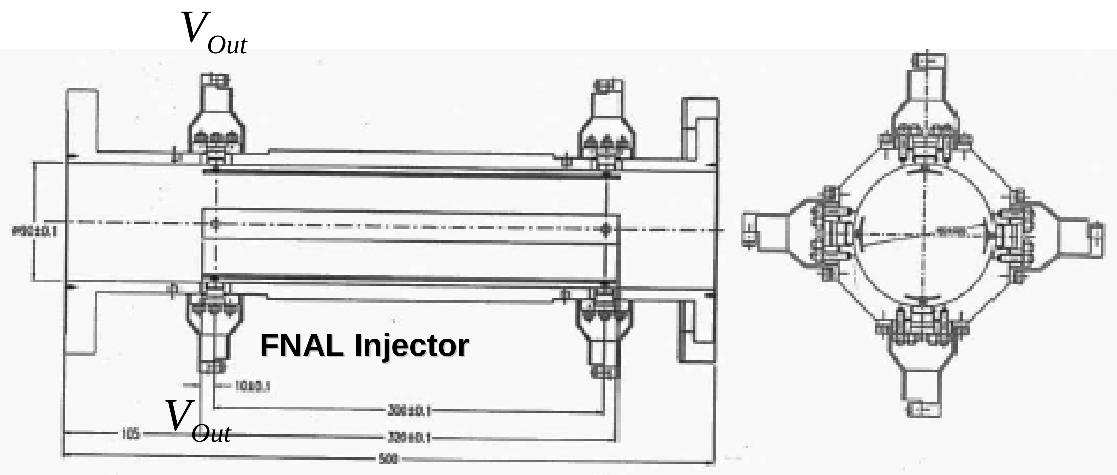


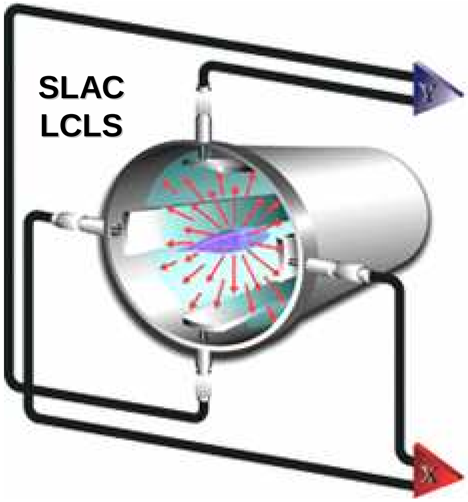
$$Usually \quad R_{L1} = Z_0 \quad and \quad R_{L2} = 0 \ or \ Z_0$$



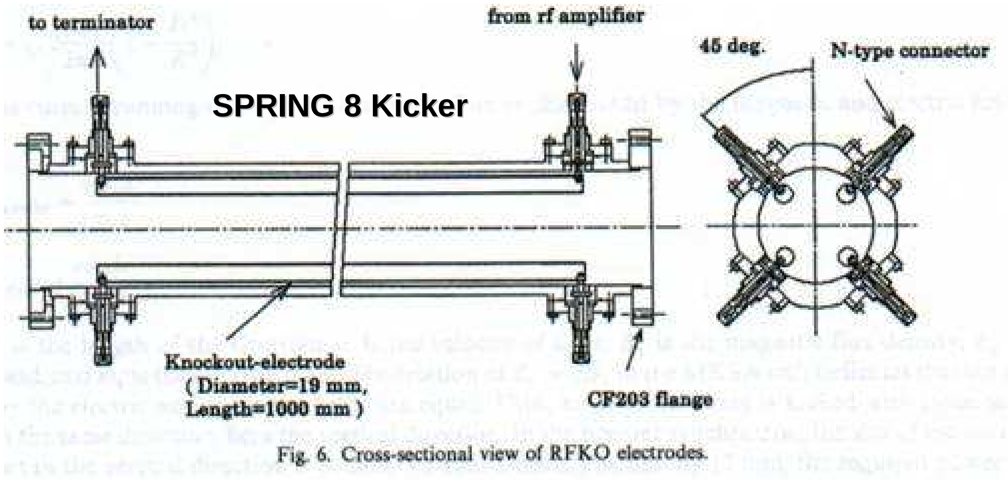
• **Transmission line type, relatively high beam impedance, high sensitivity, directionality capability, best for linacs and transferlines.**

Stripline BPM

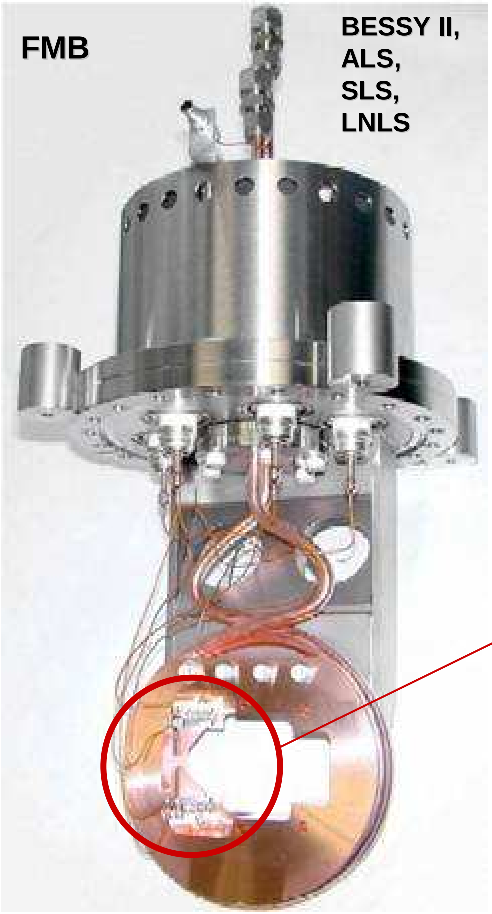




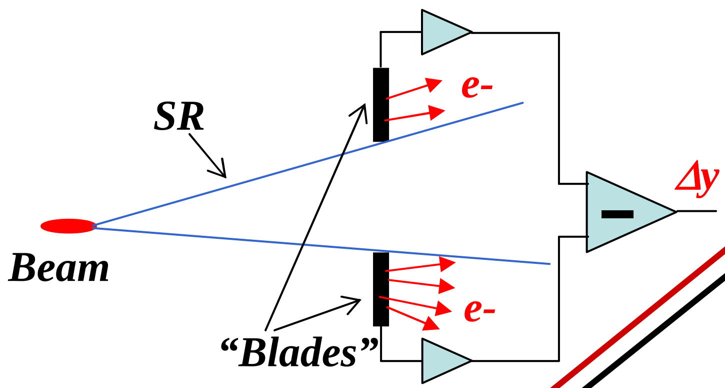
• **Stripline structures are also widely used as the "kicker" in transverse and longitudinal feedback systems.**



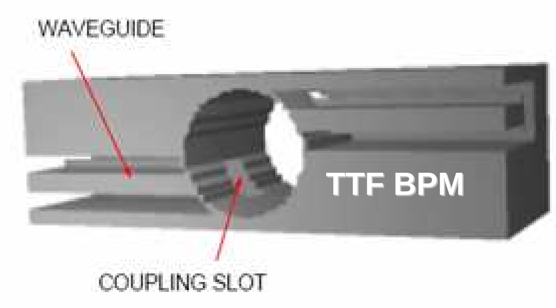
Other BPMs

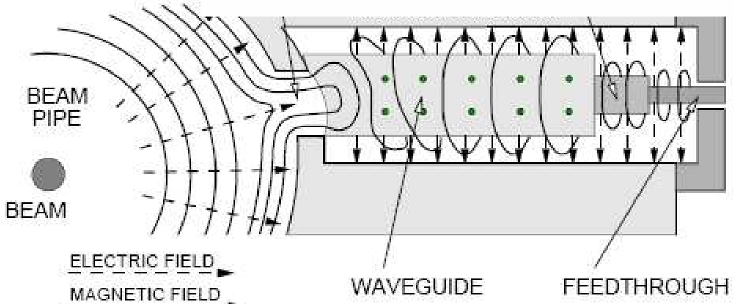


Photon - BPM



In **resonant BPMs** the beam excites modes in resonant structures

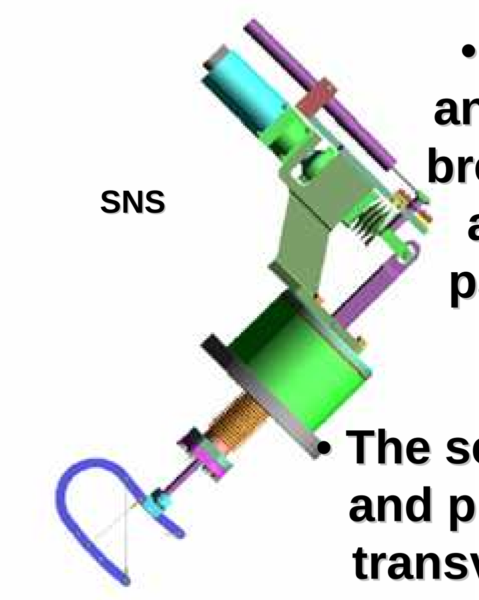




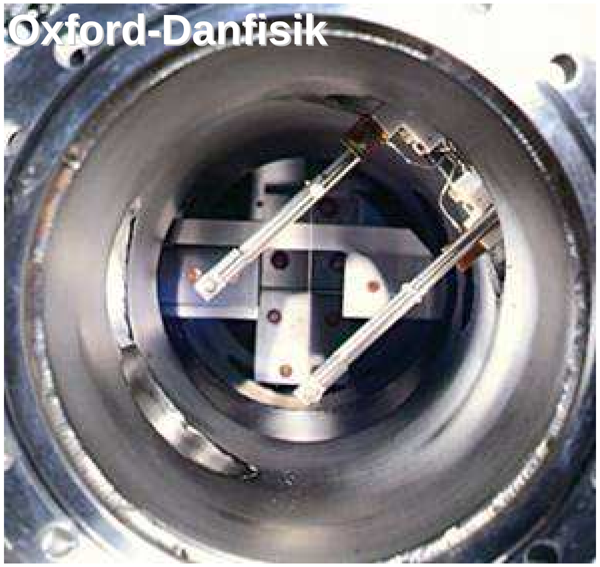
The intensity of the modes in the resonant structure is proportional to the beam offset

Beam Profile Monitors: Wire Scanners

• **A moveable wire scans the beam transversally.**

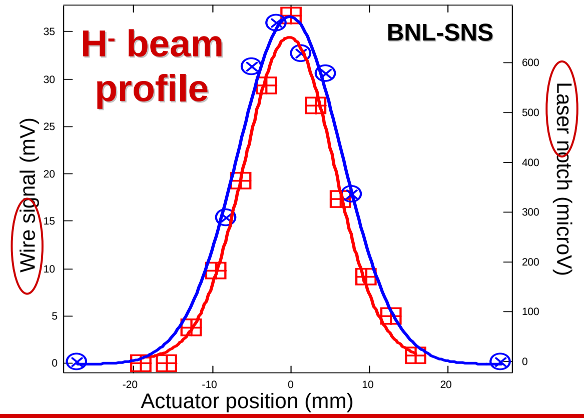


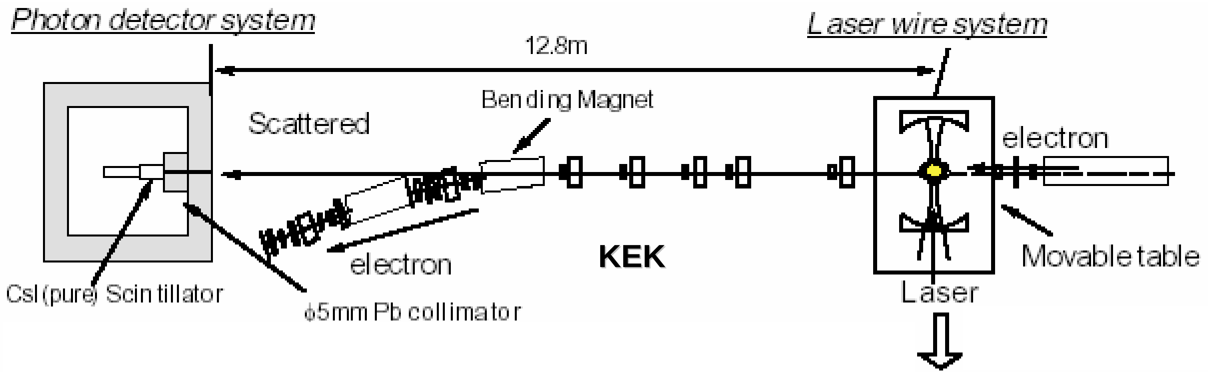
• **The interaction between the beam and the wire generates (by ionization, bremsstrahlung, atomic excitation, …) a "shower" of secondary emission particles proportional to the number of beam particles hitting the wire.**



• **The secondary particles (mainly electrons and photons) are detected and the beam transverse profile can be reconstructed.**

•**The wire material can be a metal, carbon, or … a laser beam (Compton scattering, neutralization)**

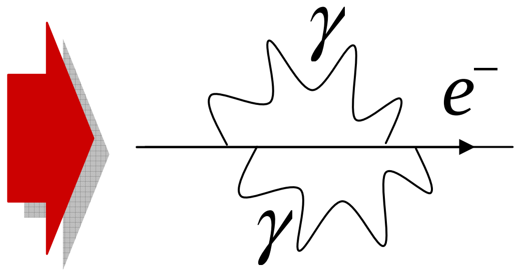




Virtual Photons

• **In the "Particle Sources" lecture, we already saw that according to quantum field theory, a photon with a large enough energy can "oscillate" between the states of virtual electron-positron pair and of real photon.**

• **The opposite is also true. An electron moving in the free space can be considered as "surrounded" by a cloud of virtual photons that appear and disappear and that indissolubly travel with it.**



• **Nevertheless, in particular situations, the electron can receive a "kick" that separates it from the photons that become real.**

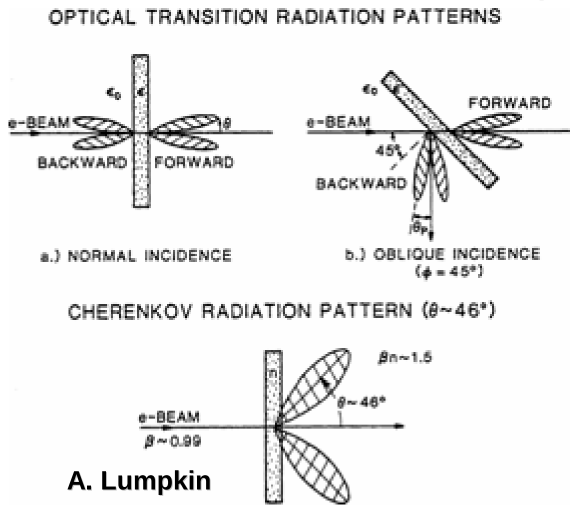
– **when the electron moves on a curved trajectory, the transverse acceleration induces the separation. This is the case of *synchrotron radiation*.**

– **when a relativistic electron moves inside a media and the speed of light in the media is smaller than the particle velocity, then the separation can happen. This is the case of the *Cerenkov radiation.***

– **when a relativistic electron moves inside a non-homogeneous media, then the separation can happen. This is the case of the *transition (diffraction) radiation*.**

Photon Based Beam Profile Monitors

- **Photon diagnostics exploiting all the described emission mechanisms are widely used for measuring the transverse and longitudinal profiles of relativistic beams.**
- **In fact, the spatial distribution of the photons reproduces exactly the particle distribution of the beam and can be conveniently used for the characterization of the beam.**
- **Monitors exploiting transition and Cerenkov radiation are relatively invasive and are mainly used in single pass or few-turns accelerators.**



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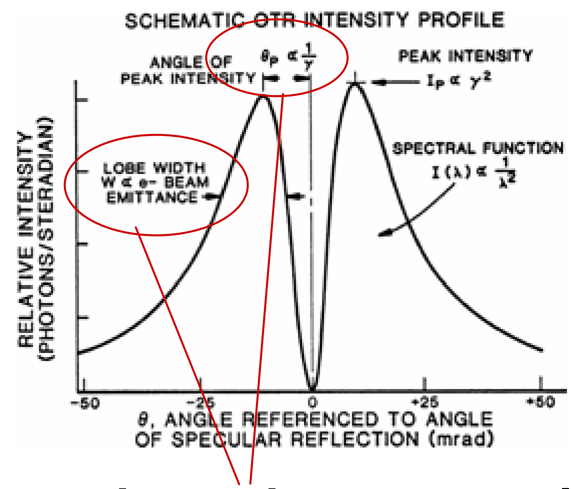
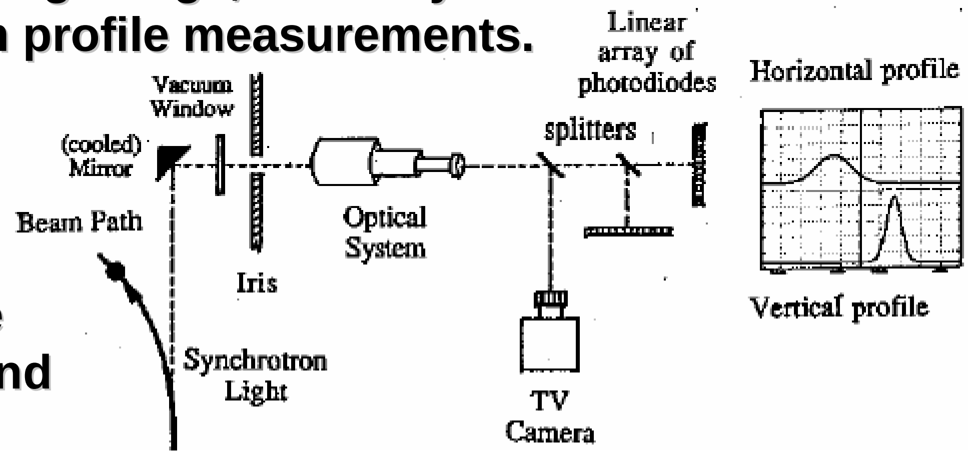


- **The angular distribution of the photons depends on several beam parameters. This fact can be exploited for the measurements of quantities other than the beam distribution as well.**

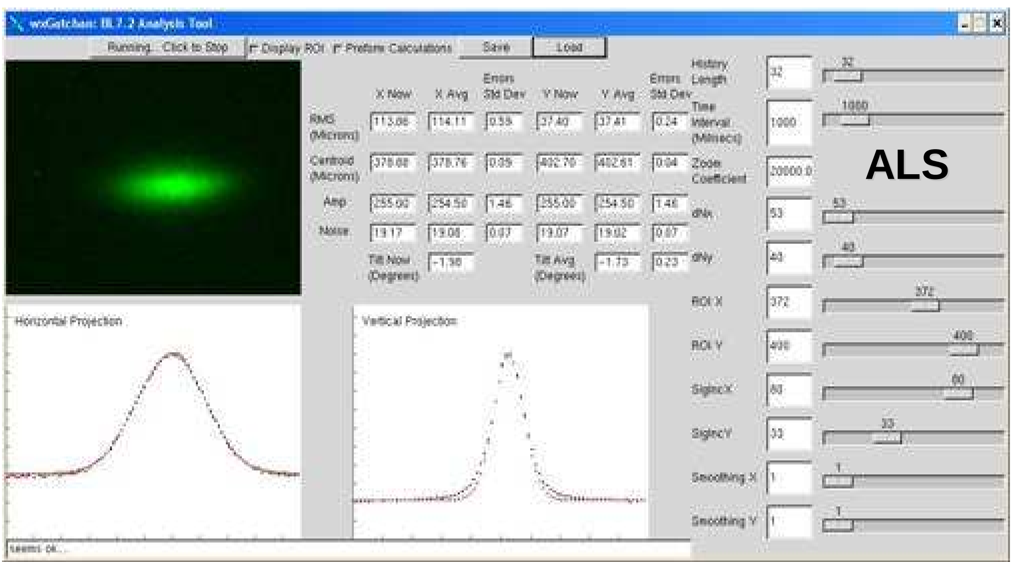
Synchrotron Radiation Monitors

- **Synchrotron radiation, very abundant in electron and positron accelerators and present in very high energy proton storage rings, is widely used for transverse and longitudinal beam profile measurements.**



- **One of the appealing features of such diagnostic systems is that they are non-invasive.**

- **The resolution of these monitors are limited by the geometry of the system and by the radiation diffraction.**



- **The geometric limitation requires small aperture systems while the diffraction term requires large apertures and shorter photon wavelengths. Tradeoff solutions must be adopted.**

- **Typical resolutions in electron storage rings using hard x-ray photons range between few and tens of microns.**

Other Beam Profile Monitors

• The simplest beam profile monitor is probably the one using fluorescent screens intercepting the beam.

• The beam particles hitting the screen material excite the atoms that subsequently radiate a photon in the visible range when decaying back to the ground state.

• The resulting image of the beam on the screen is then viewed by a ccd camera and eventually digitized by a frame grabber for further analysis.

• Such monitors are destructive and typically are used only in beam transferlines.

•Another category of beam profile monitors are the ionization chambers.

• In this monitor, a gas in a dedicated portion of the vacuum chamber is ionized by the passage of the beam.
Depending on the scheme used, either the electrons or the ionized atoms can be detected for the beam profile reconstruction. Time of flight analysis of the ionized particles are usually necessary.

• Because of their perturbative nature, these monitors are mainly used in single pass accelerators.

Photon-Based Longitudinal Profile Monitors

• **In photon-based longitudinal beam profile monitors, detectors such as *streak cameras*, *fast photodiodes and photomultipliers* are used.**
In the streak camera case, time resolution of several hundreds of fs can be achieved.

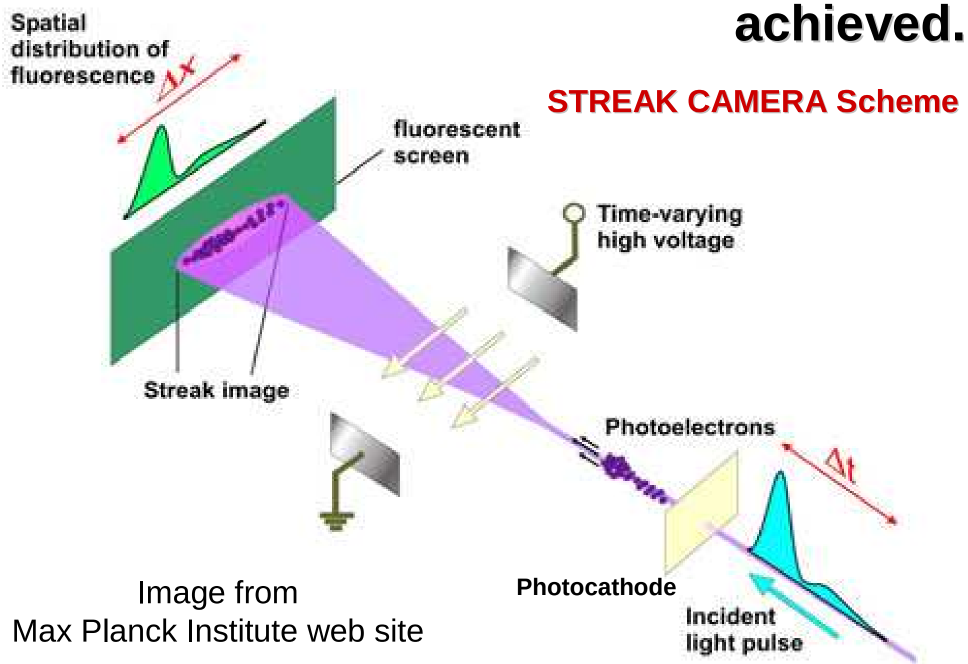
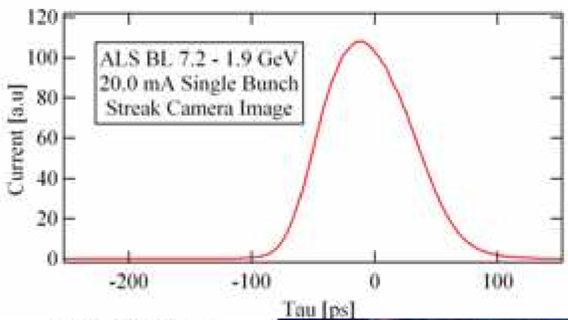
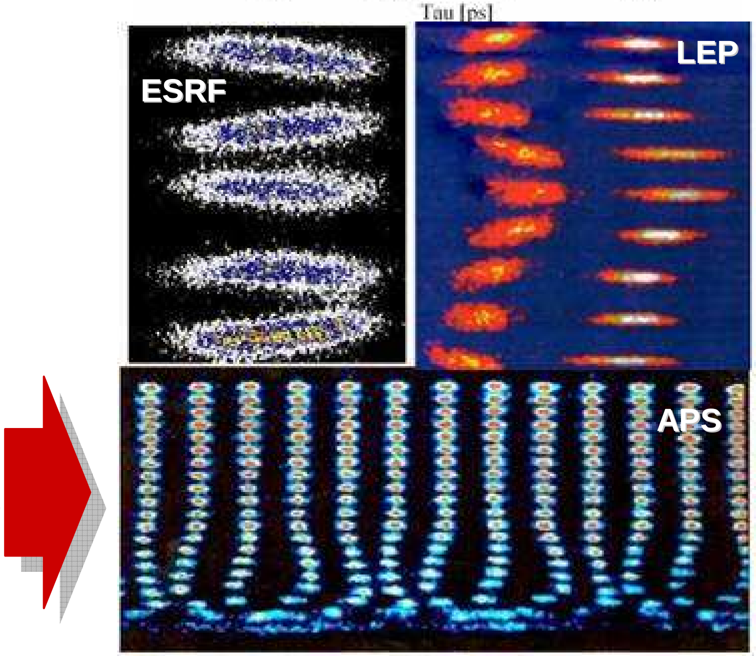


Image from
Max Planck Institute web site

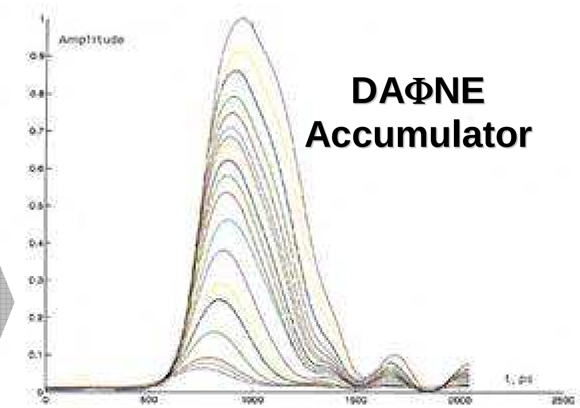


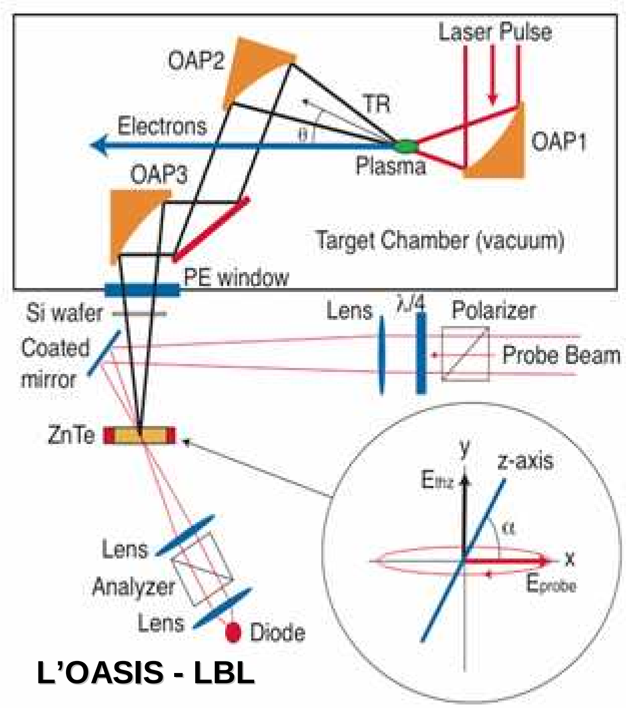


• **Streak cameras with an additional couple of sweeping electrodes (orthogonal to the other one) have single bunch-single turn capabilities and can be used for the characterization of single and multibunch intabililities.**

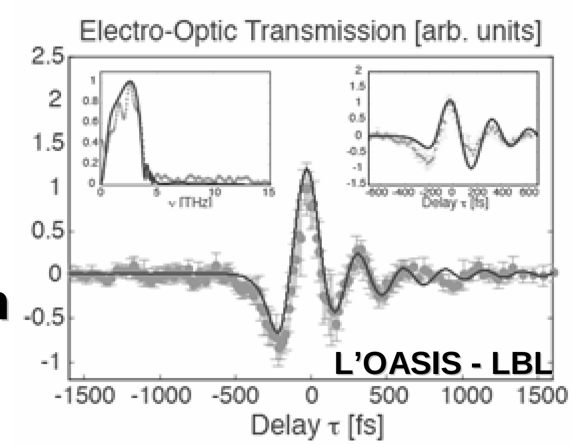
More on Longitudinal Profile Monitors

- **For relatively long bunches ~ 100 ps or longer electromagnetic pickups can be efficiently used.**
- **In this example, the beam inside the DAΦNE Accumulator (~ 150 ps rms) is measured by using the signal from a stripline.**



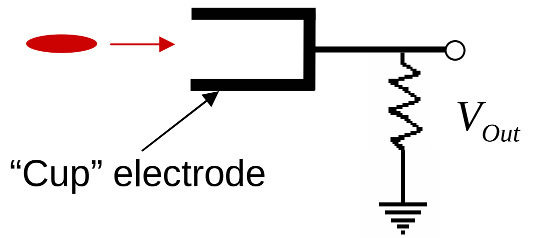


- **Femtoseconds resolution (or even smaller) can be achieved by interferometric techniques involving coherent light in the Far-IR (coherent synchrotron radiation, coherent transition radiation, …) or by electro-optic techniques using non-linear crystals and laser probing.**



Current Monitors: Faraday Cup and Current Transformers

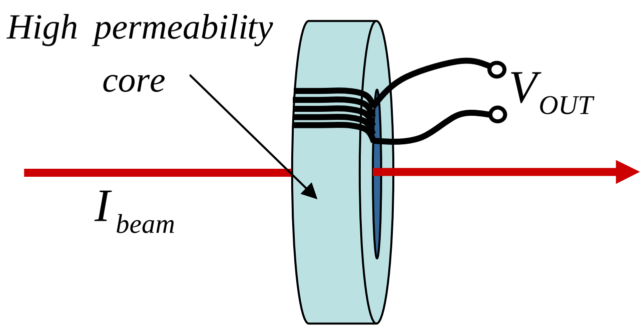
• Conceptually, the **Faraday cup** is the simplest among the current monitors.

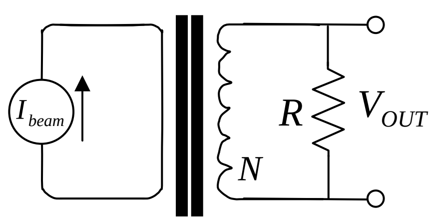


• Electrostatic fields with the proper sign can be added in order to avoid that primary and secondary (emission) charged particles can leave the cup affecting the measurement.

• For short bunches, if the shape of the bunch needs to be measured as well, the FC has to be designed as a transmission line in order to present a good high frequency response.

• **Current transformers** are used for measuring the AC component of the beam current:

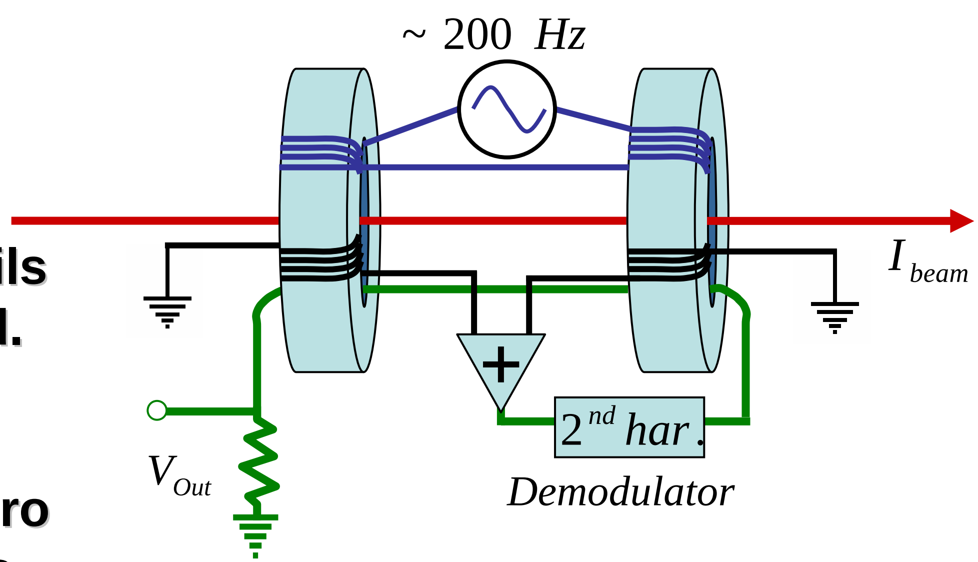




$$\boxed{V_{OUT} = \frac{R}{N}\frac{i\omega L/R}{1+i\omega L/R} I_{beam} \cong \frac{R}{N} I_{beam} \quad for \quad \omega >> \frac{R}{L}}$$

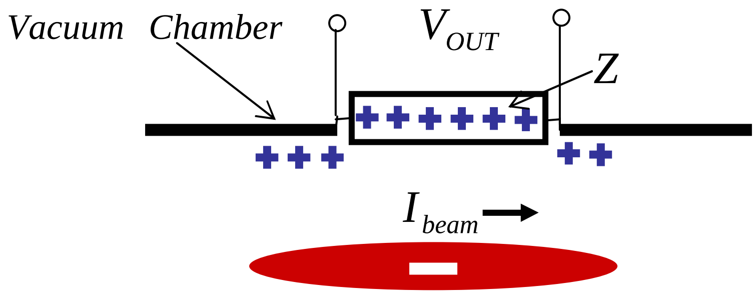
Beam Current Monitors: The DC Current Transformer

- For measuring the average beam current (DC component), the **parametric current transformer** or **DC current transformer** (DCCT) is used:
  - The DCCT uses two high permeability cores driven to saturation by a low frequency current modulation.
- The signals from two secondary coils of the cores are mutually subtracted.
  - Because of the non-linear magnetization curve of the core material, this difference signal is zero only when the beam current is zero.



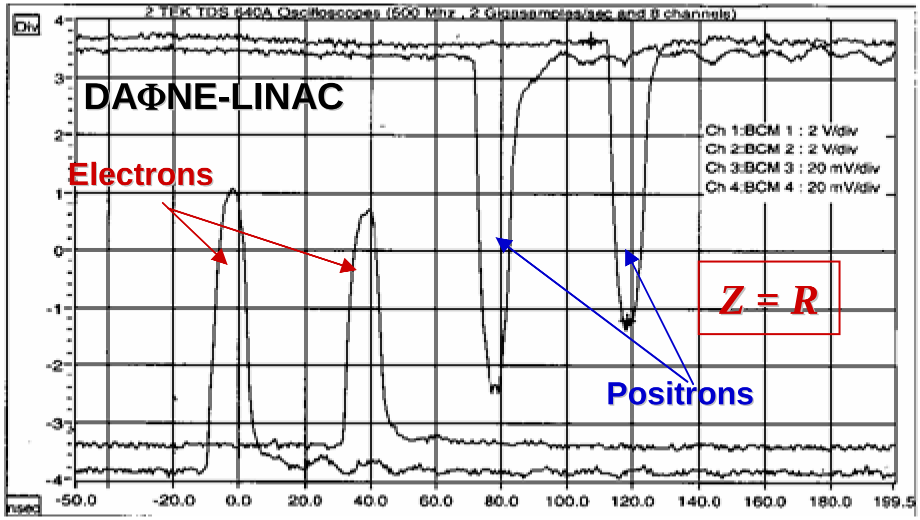
- In the presence of beam current this difference signal is non-zero and in particular shows a second harmonic component.
- A current proportional to the amplitude of this component is fed back into a third coil in order to compensate for the beam current and to make the difference signal zero.
- At equilibrium, the current flowing in this third coil is equal in amplitude to the beam current but opposite in sign.

Beam Current Monitors: Wall Current Monitors.

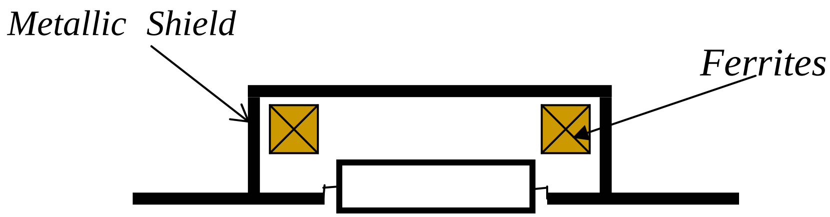


$$V_{OUT} = Z\, I_{beam}$$

- The band-width of such monitors is limited to few GHz.
- Additionally, in the described configuration they can radiate and/or pick-up high frequency electromagnetic noise.

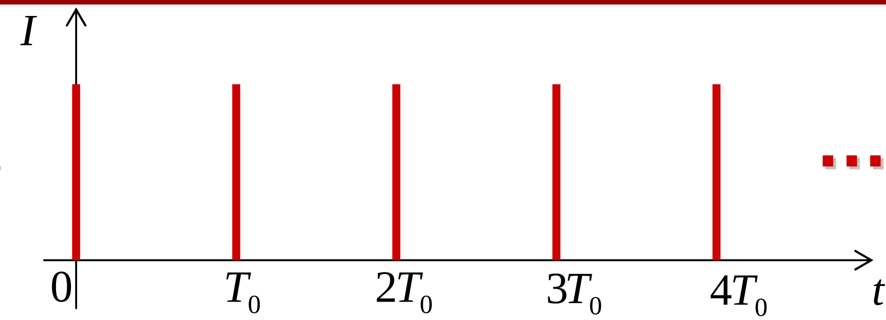


- For limiting such a noise, a metallic shield loaded with ferrites (inductive loading) can be used.

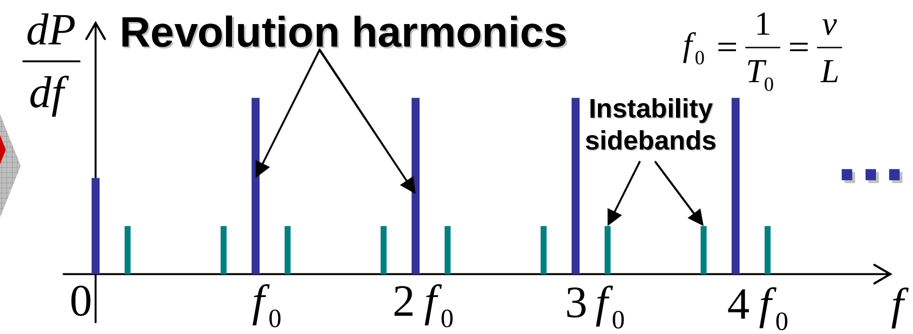


Beam Spectrum

- **By detecting the passage of a particle at a fixed azimuthal position the following time domain signal can be observed.**



- **By Fourier transforming or by using a spectrum analyzer, the same signal in the frequency domain will appear as:**



- **In the presence of betatron and/or synchrotron oscillations, sidebands around each of the revolution harmonics will appear at the frequencies:**

$$f_S = nf_0 \pm fractional \;\; part \;\; of \;\; Q_w \qquad w = x, y, s$$

- **In the case of a multi-particle beam, because of the non-zero momentum spread and machine non-linearities, the particles have slightly different oscillation frequencies. As a consequence the spectral lines will show a finite thickness.**

Schottky Noise Monitors

• By using resonant electromagnetic pick-ups (cavity or waveguide) the signal resulting from the motion of all the particles can be detected.

• Because the motion of the particles is essentially independent, such a signal appears as a noise and it is usually referred as the Schottky noise (SN). SN find applications in beam diagnostics

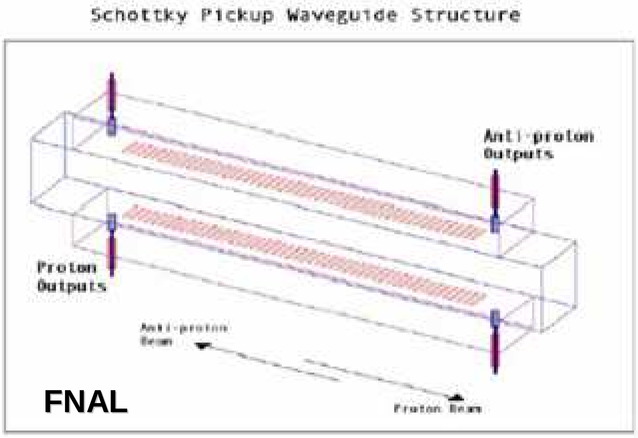
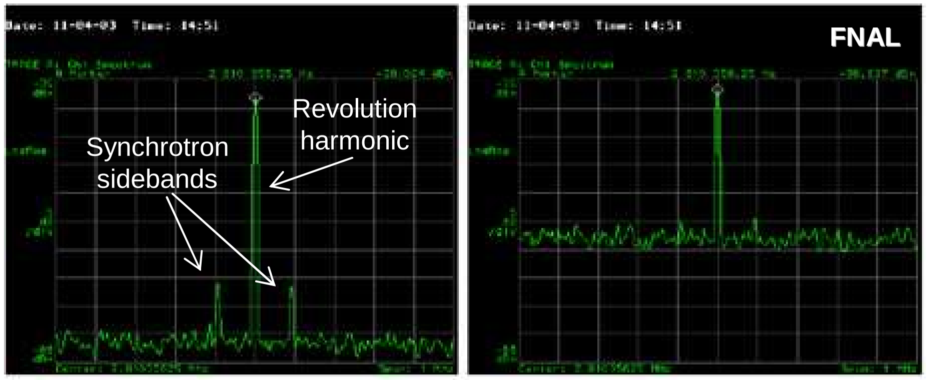


Fig. 2. Waveguide structure

• In fact, Schottky noise monitors are actually the main non-invasive diagnostic tool used in heavy particle storage rings. Quantities that can be measured include longitudinal and transverse tunes, momentum spread and beam current.



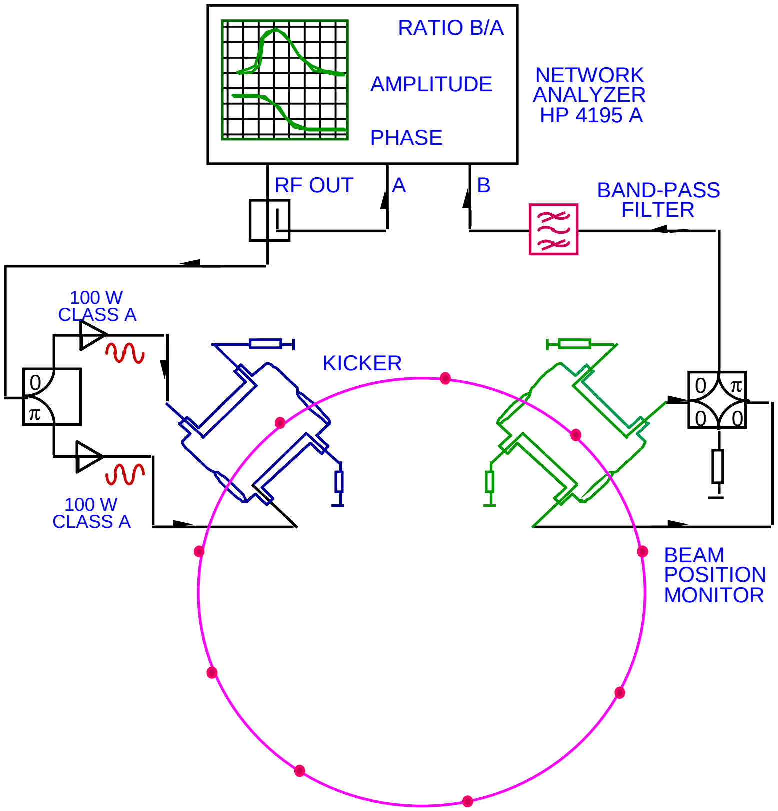
Horizontal Anti-proton Sum

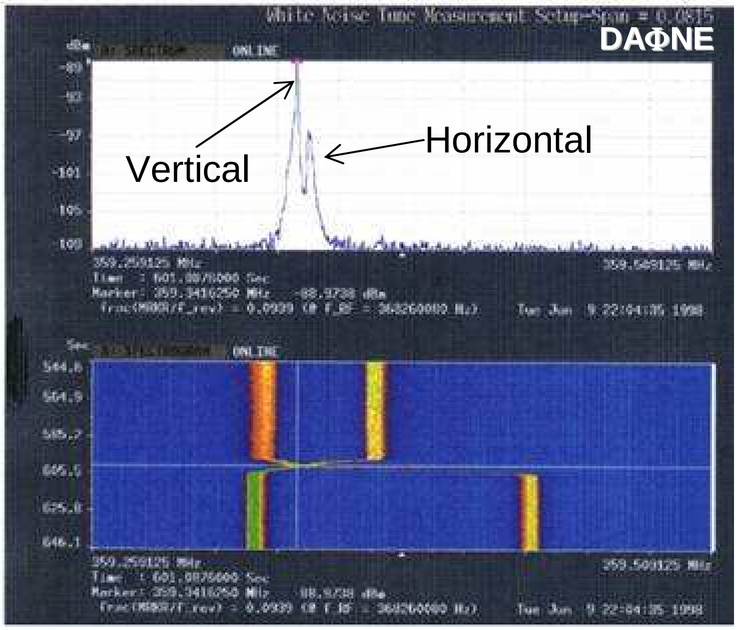
Horizontal Anti-proton Delta

• Schottky noise cannot be used in electron and positron machines because in those accelerators, the noise due to synchrotron radiation quantum fluctuations is strong and covers the Schottky noise.

Tune Measurement

• **In electron and positron machines, in order to measure the betatron tunes in the absence of instabilities, coherent beam oscillations need to be excited.**





• **Synchrotron tune can be measured by modulating the RF phase or amplitude and by measuring the induced sidebands using the sum signal from a pick-up.The same detection part of the betatron tune measurement system can be used.**

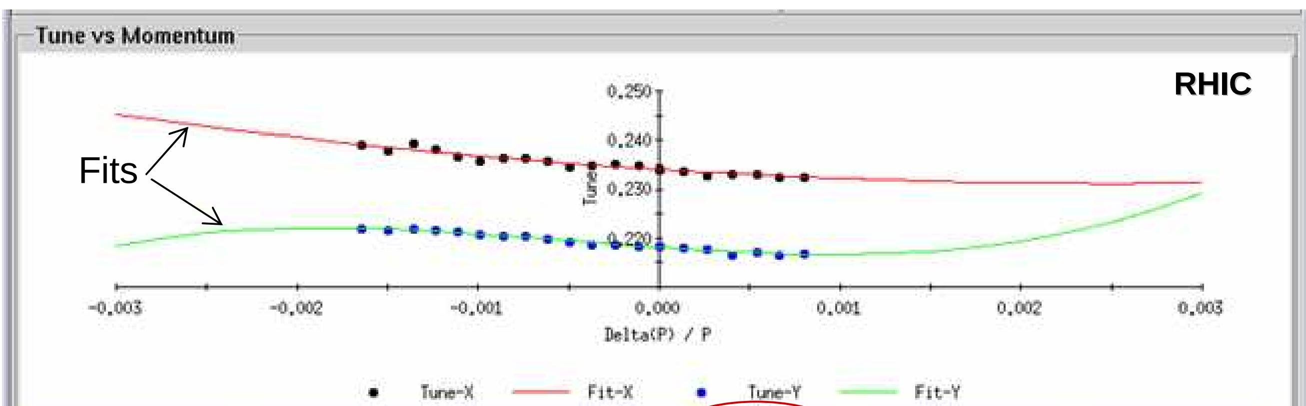
Beam Characterization: Chromaticity Measurement

Chromaticity is measured in storage rings by changing the momentum (energy) of the beam and by recording the induced tune variations.

$$\xi_w = \frac{\Delta Q_w}{\Delta p / p_0} \qquad w = x, y$$

The beam momentum is usually changed by varying the RF frequency. In this way, the revolution period is modified and the particles are forced into trajectories with different curvature in the dipole magnets. This can happen only if the particles change their momentum.

$$\frac{\Delta p}{p_0} = \frac{1}{\eta_C}\frac{\Delta L}{L_0} = \frac{1}{\eta_C}\frac{\Delta T}{T_0} = -\frac{1}{\eta_C}\frac{\Delta f_0}{f_0} = \frac{1}{\eta_C}\frac{\Delta f_{RF}}{f_{RF}}$$



Type\Term	Error	Tune	Chromaticity	Chrom[2]	Chrom[3]
Horizontal	4.90197e-06	0.234112	-2.32443	465.52	-803.944
Vertical	1.48313e-06	0.21818	-2.6326	630.557	489049

The experimental data are fitted by a polynomial function. The fitting function calculated at the nominal momentum gives the linear chromaticity.

Orbit Measurements

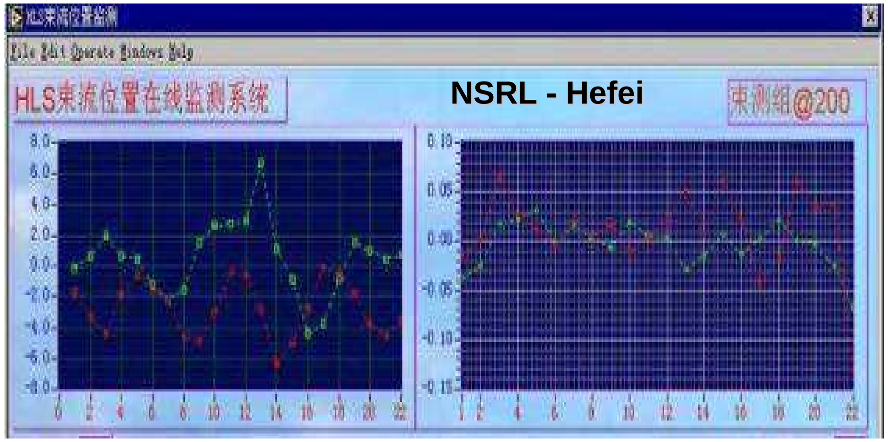
• In most of acceleration applications, the beam orbit needs to be very stable. In colliders, counter-rotating beams with transverse size in the nanometer scale need to overlap for collision, while in light sources orbit stability requirements are often on the order of a micron.

• We saw how accelerator imperfections can generate orbit distortions.

• Such orbits need to be carefully *measured* and *corrected*. In addition, orbit feedbacks are often used to ensure the required stability.

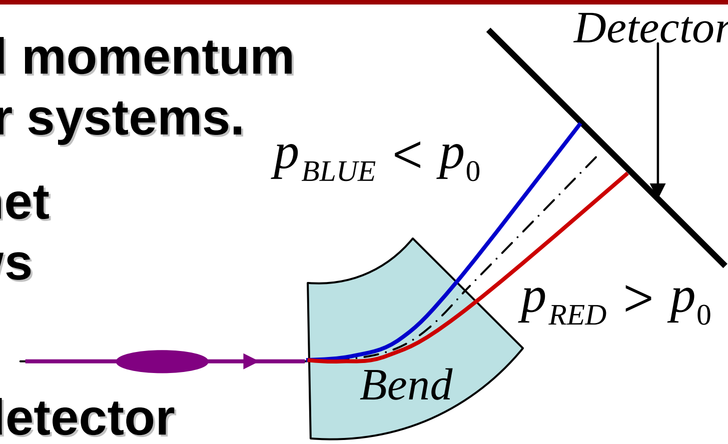
• In circular machines, the transverse beam trajectory can be approximated by a sinusoid oscillating at the betatron frequency. Nyquist theorem states that we need to sample the orbit in a number of positions at least twice the betatron tune number. With some contingency, at least four BPMs per 2π betatron phase advance are used in circular and linear accelerators.

• Absolute orbit measurements suffer of accuracy limitations. In fact, the actual center of magnets and BPMs is not exactly known. Measured closed orbits are often referred to a “golden orbit”, which is usually obtained by the *beam-based* alignment of the beam to the center of the quadrupoles.



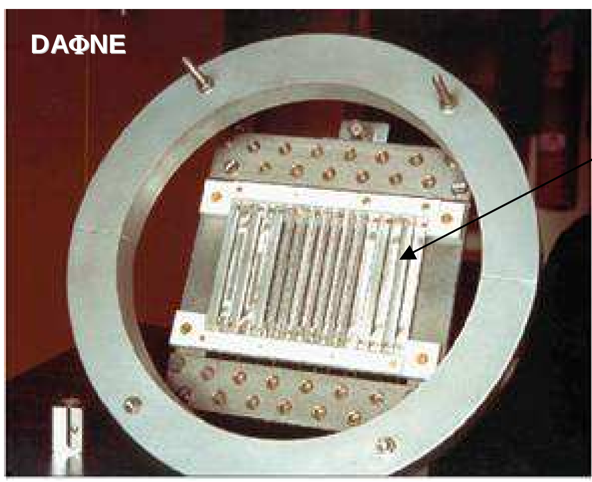
Momentum and Momentum Spread Measurement

- In linacs and transferlines the momentum and momentum spread are mainly measured by spectrometer systems.



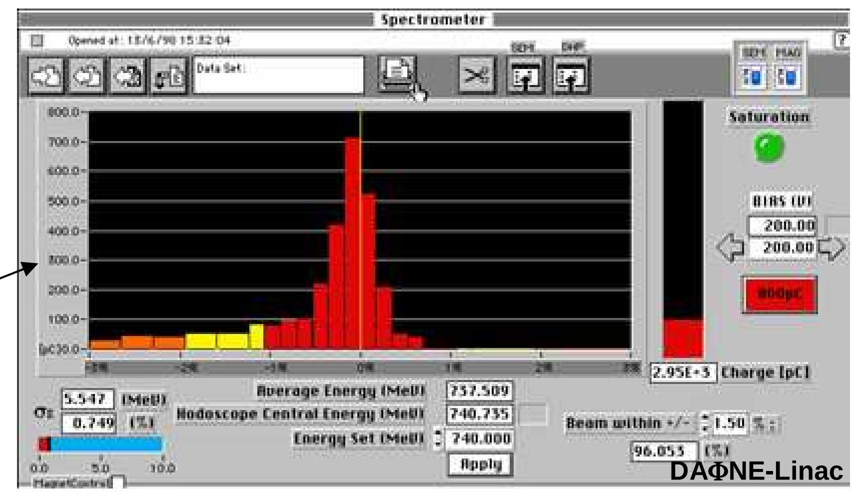
- The beam enters in the field of a dipole magnet where particles with different momenta follows different trajectories.

- The particle position is then measured on a detector downstream the magnet.



Secondary emission hodoscope

Spectrometer control window



- The spectrometer resolution is limited by the intrinsic beam size at the detector plane and by field non-linearities.

Momentum Spread & Emittance Measurement in Rings

- **In electron and positron storage rings the equilibrium beam emittance and the momentum spread can be measured by the combined measurement of at least two transverse beam profiles at two different ring locations.**

- **The beam size at a particular azhimutal position is given by:**

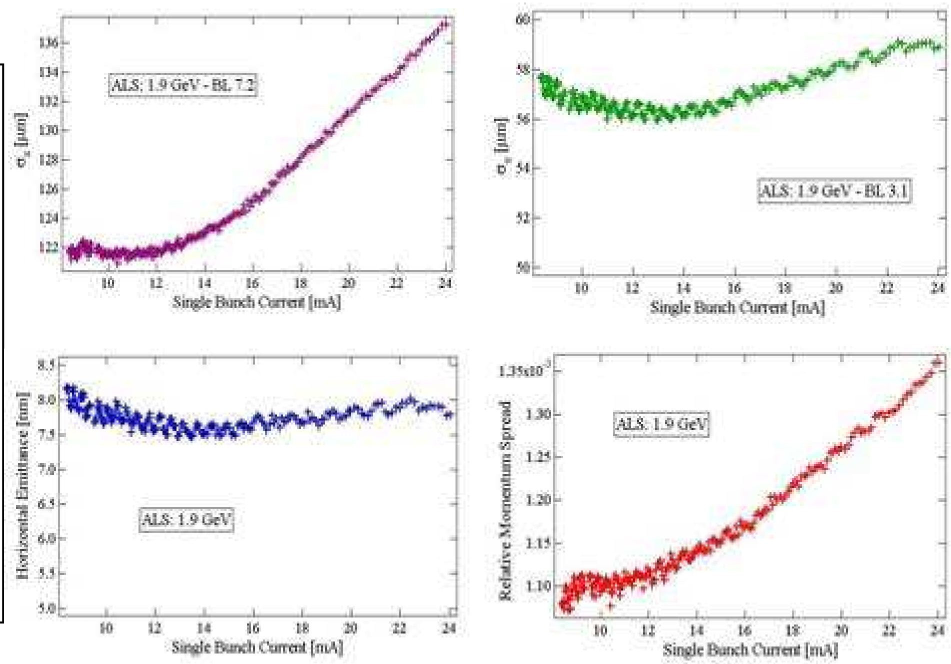
$$x_{rms\,i} = \left(\beta_{xi}\varepsilon \frac{1}{1+\kappa} + \left(\eta_{xi} \frac{\sigma_p}{p} \right)^2 \right)^{1/2} \qquad i \equiv system\ index = 1,\ 2$$

- **If the beam size is measured in two different points of the ring and the optical functions at such points are known, then:**

$$\varepsilon_x = \frac{\varepsilon}{1+\kappa} = \frac{x_{rms1}^2 \eta_{x2}^2 - x_{rms2}^2 \eta_{x1}^2}{\beta_{x1}\eta_{x2}^2 - \beta_{x2}\eta_{x1}^2}$$

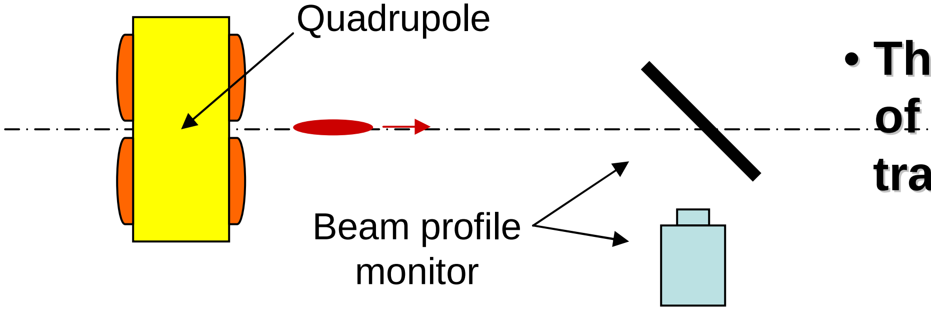
$$\left(\frac{\sigma_p}{p} \right)^2 = \frac{x_{rms2}^2 \beta_{x1} - x_{rms1}^2 \beta_{x2}}{\beta_{x1}\eta_{x2}^2 - \beta_{x2}\eta_{x1}^2}$$

ε:	emittance
p:	momentum
β:	beta function
η:	dispersion
κ:	emittance ratio
x_{rms}:	rms beam size



Emittance Measurement In Linacs and Tranferlines

• A "popular" technique for measuring the emittance in linacs or transferlines uses the so-called "three gradient method".



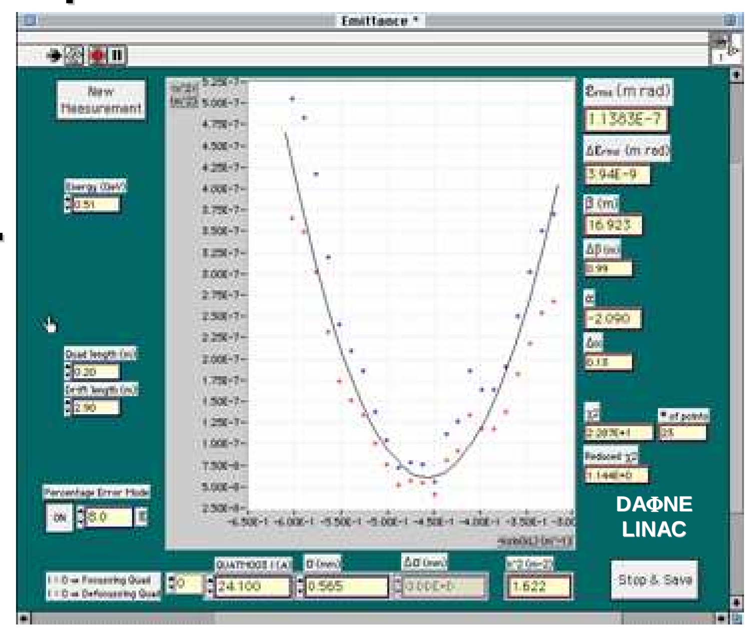
• The gradient (focusing-defocusing strength) of a quadrupole is changed and the related transverse beam profiles are recorded by a detector downstream the quadrupole.

• The measurement requires a minimum of 3 different quadrupole gradients but the accuracy can be improved if more points are taken.

• The beam size at the detector is defined by the beam emittance and by the local beta function. The emittance is an invariant while the beta changes with the changing quadrupole gradient.

• An analytical expression linking the transverse profiles with the beam emittance can be derived and used for fitting the experimental data.

• From the fit, the values for the emittance and for the optical functions at the quadrupole position can be finally extracted.



More Measurements

• ***Optical function measurements*: by single quadrupole gradient perturbation, by phase advance between position monitors, by response matrix, by energy momentum variation for dispersion function measurement, …**

• ***Non-linearities and dynamic aperture measurements*: by kicking the beam transversely and characterizing the tune shift on amplitude, by frequency map analysis, by de-coherence measurements, …**

• ***Transverse coupling measurements*: by transverse beam profile monitors, by response matrix, by closest tune approach, …**

• ***Momentum acceptance measurements*: by changing the particle momentum in combination with lifetime measurements, by modifying accelerator parameters for discriminating among different contributions, …**

• ***Coupling impedance measurements*: by characterizing the tune shift on current, by measuring instability thresholds, by energy spread measurements, …**

• ***Lifetime measurements*: by current monitors, by beam loss monitors, by modifying beam parameters in order to discriminate among different contributions, …**

• **…**

References

R. Littauer, “Beam Instrumentation”, Proc. Physics of High Energy Particle Accelerators (Stanford, CA, 1982); AIP Conf. Porc. 105 (1982) 869.

M. Serio, “Diagnostica e misure”, Seminars on DAΦNE, February 2000.

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M. Minty, “Diagnostics”, CAS Synchrotron Radiation and Free-Electron Lasers, Brunnen, Switzerland, July 2003.

Possible Homework

- A misaligned quadrupole in an electron storage rings with 5.2 horizontal tune generates a horizontal closed orbit distortion of 2 mm at its own position. Calculate the kick that a corrector magnet inside the quadrupole needs to apply for correcting the orbit. The horizontal beta at the quadrupole is 3 m.
- Calculate the length of the detector of the FNAL Injector stripline in the figure on the "stripline electrode" viewgraph.
- Describe the shape of the pulse from a matched stripline of 5 cm length detecting a uniform distributed beam with 2 ns total length.
- Define the electronic circuit equivalent to a resistive wall current monitor with a ferrite loaded shield. Calculate the frequency response of such a monitor.